Enabling Organizational Innovation: Scientific Process and Military Experience

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Abstract

Increasing information richness and the changing socio-political environment in recent years have resulted in changes in corporate structure and organization. The growing challenges of organizational and technological complexities require the development of new organizational concepts. The effects of a combination of high complexity and high uncertainty have been recognized before in military settings. To take advantage of new technologies and manage information complexity, a theory of Network Centric Operations was developed. Mission Command and Network Centric Operations formulate organizational structure across functional domains (physical, informational, change this cognitive and social), in a way that is also applicable in a business setting. In response to an increase in decision complexity and regulations, academia has developed risk assessment and multi criteria decision analysis tools for use in military and industrial settings. We believe that the combination of military science with multi-criteria decision analysis and risk assessment has the potential to dramatically improve the credibility, efficiency and transparency of strategic and tactical decisions in industrial settings. This paper summarizes the military concepts of MC and NCO, and links them with mental modeling, risk assessment and decision analysis tools. Application of the combined framework for the pharmaceutical industry is also discussed.

1. Introduction

The ability to make good decisions and communicate their impact is crucial to any business. Providing timely, clear direction based on the best available information is at the heart of both setting and achieving an organization's aims. Indeed, the ability to consistently make the right decision at the right time can be a significant competitive advantage. Although perhaps an obvious statement, it is important to remember that the operational implementation of a strategy requires a decision-maker to guide the application of people and materials to a process, through the collection, analysis and use of information. As information sources and volumes continue to multiply, the certainty that a decision is being based upon the right and best available information decreases – the paradox of uncertainty caused by too much information. that may or may not be relevant to any given decision, resulting in an increased uncertainty as to the sound footing of any decision.

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14. ABSTRACT

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Today's competitive business environment requires jointness in internal communications and operations, and must be tempered by an understanding of the mental models of internal and external stakeholders as well as the social, cultural, and technological challenges of bringing new products and services to market. The concept of multi criteria decision analysis offers a framework for surfacing and balancing the various perspectives and requirements of each stakeholder, and to consider which information is of most importance in agreeing a course of action.

In the traditional hierarchical, 'full service' model of a business, decision-makers could at least feel they had some level of control over the implementation of their decisions across the entire research, development, marketing, sales and supply chain processes. A hierarchical structure promising long-term employment and well-established career paths maintained a strong link between employee and employer, so that a company could to some extent rely on a loyal workforce as a foundation for developing its business.

Industry globalization, new business models and a changing workforce make traditional hierarchical organizational models less efficient in executing strategic and operational plans. . As more and more companies seek to focus on their core value proposition, networks of partners and suppliers make major contributions not only to manufacturing a company's new products but to the research, development and marketing of those products. The relationships that occur in an outsourced business model introduce a greater level of complexity to the implementation of a strategy. Business development leaders, managers, and scientists are increasingly involved in operations where they must make real-time decisions in the context of a combination of the internal cultural context and those of external stakeholders (e.g., governmental agencies, industrial partners, and customers).

At the heart of effective operations in new product development is an organization's ability to reconfigure quickly to exploit an opportunity, whilst retaining a robust decision-making framework that ensures overall clarity.

The rise of the dispersed collaborative model of business, now often referred to as Open Innovation, introduces greater complexity to the organizational management. It requires a different way of thinking about how an organization coordinates activities to deliver and derive value from a final product or service. Relationships within such collaborations occur on many levels at the same time; between the corporate entities, principal officers, project teams, accounting departments, lawyers etc. Research partners may become competitors based on the output of their research (e.g Schlumberger in the Oil & Gas industry). Competing companies may be linked by a common partner that must work with each of the competitors in their own way, with very different procedures and performance expectations.

The effects of a combination of high complexity and high uncertainty have been recognized before in military settings. The breakthrough technologies the world has experienced in the last three decades have brought military organizations to some radical thinking on how to increase the organizational effectiveness and remain relevant in a changing world. Military organizations are commonly perceived as conservative, hierarchical, rigid, and command control oriented. [1] In fact, although some of these attributes do exist in parts of military organizations for historical and other reasons, there is also another side of the military which is less known: an innovative and adaptive one. Military organizations are dealing with what is probably the most difficult task: wining battles and wars. Fighting wars can be a very messy and complicated thing; anything can and will happen. Clausewitz, the great war philosopher, described war as the 'kingdom of uncertainty', a place which is characterized by a 'clash of wills'.

The organizational concepts of Mission Command and Network Centric Operations that have emerged in the military have important implications for dealing with complex and uncertain environments, not only for military organizations but also for large organizations in general. This paper links military concepts with methods and tools of real or near-real time decision making (risk assessment, mental modeling and Multi-criteria Decision Analysis). The methodology we propose provides the ability to establish and maintain clarity of understanding and communication across multiple relationships, whilst preserving the flexibility and agility necessary to meet changing needs.

2. Military Concepts

Military organizations have dealt with decision and management complexity for a long time. Whilst we acknowledge that many theories and approaches to dealing with complexity have been developed by military science, we are focused on the concepts of mission command and network-centric operation because of their specific applicability to emerging industrial . Mission command (MC) involves the assignment of a mission or task, rather than a set of instructions, to a subordinate. The subordinate then analyses the mission, having been provided with a framework of understanding or context and the support/resources needed to succeed. Network Centric Operations (NCO) offers a new form of organizational behavior that seeks to translate an information advantage, supported by technology, into a competitive advantage through robust networking.

2.1 Mission Command

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[1] The term itself 'command and control' is a military term, and is commonly used in business in a negative connotation which implies strict management rules imposed from above and micromanaging.

Mission command, or as it has been known in its German name *Auftragstaktik,*[2] is a decentralized leadership and command philosophy that demands and enables decision and action in every echelon of command where there is an intimate knowledge of the battlefield situation. Mission command derived from the original German concept, *Auftragstaktik*, is believed to have been initially developed by the German army in a gradual process, following the shocking defeat of the Prussians in Jena by the innovative army of Napoleon. It calls for subordinates to exploit opportunities by being empowered to use their initiative and judgment, as long as their decisions serve the higher objective communicated to them prior to the mission, which is referred to as *intent*. It is based on the belief in the ability of an individual to act wisely and creatively in order to solve a problem without having to resort to higher authority.

Mission command aims to avoid the drawbacks of centralized systems, which suffer frequently from a lack of flexibility and responsiveness. It also helps avoid the usual shortcomings of decentralized systems, that is, the lack of coordination and control. Through the use of the higher *intent* as a coordination mechanism, it goes beyond simple decision delegation and empowers subordinates; it provides a flexible framework that allows the exploitation of opportunities while maintaining the overall purpose of a military operation.

A key element in the success of this approach is the articulation and communication of the commander's *intent*. This is done through a framework for meaningful reception and dissemination of information which forces the superior commander to assess information and to convert it into a plan or idea, often refer to as a *concept of operation,* and then translate it into orders that reflect his chosen *course of action* in a way that is easily communicated and executed. The executed plan is then under constant revision and alteration according to the ever-changing situation, but these changes are always done according to the higher *intent*. This enables flexibility and responsiveness.
Mission command is an approach designed to deal with complex systems, large amounts of information and an ever-changing environment. It is not easy to understand or to carry out, and its implementation might run contrary to basic existing organizational cultures. It requires above all a shared doctrine, trust which implies tolerance for learning and latitude for honest mistakes, professionalism and inclination for initiative.

Mission command is based on the following basic dictums regarding the nature of warfare and human behaviour:
- The complexity and chaotic nature of the battlefield - what Clausewitz called fog of war', 'friction' and 'uncertainty' - are an integral part of warfare and should be taken into account.
- Commanders and managers are leaders of complex systems; their mission is to understand how complex systems work through the idea of intent and thus be able to optimise subunits to produce the best result to support the system as a whole.
- Time is a critical factor: in low tactical levels the commanders must act within a

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[2] There are a number of translations often used (mission type orders, directive control) . The term used here is the most common one: mission command, it is the one used in the American Army official doctrine papers (FMs)

very short time frame, and decision making cycles must be quick.

- Limitation of span of control, the best commander has nevertheless a limited capacity for information processing, therefore a necessity to share the burden with a limited number of subordinates.
- Technology, regardless of its sophistication, cannot make judgement calls or generate creativity as this capacity is uniquely human. Technology can only enhance communication and more efficiently process information.
- Better motivation and commitment is gained through active participation and an individual sense of executing one's own ideas and plans.
- As long as these will continue be true so does mission command effective application in organization.

In the post World War II years following the defeat of the German Army, mission command was somewhat neglected. During the years of the Cold War, the West, facing the Soviet threat, was searching for ways to balance its relative quantitative inferiority. In its investigation to explore the fighting qualities of the *Wehrmacht,* it discovered mission command as a central virtue that gave the Germans an edge over their rivals. More specifically, it was viewed as a major principle to enable a fast Observe Orient Decide Act (OODA) loop principle which was developed by John Boyd which emphasised the importance of quick adjustment of decisions and executions to changing situations. Mission Command was first officially incorporated into the US Army 1982 Doctrine, known also as the *AirLand* Battle which emphasized four main tenants: *agility, depth, initiative* and s*ynchronization*.[3] This doctrine was put to effective use in the first Gulf War 1991. Since then it has been adopted by all NATO members and continues to be a central command approach in all major military doctrines.[4]

2.2 Network Centric Warfare (NCW)[5]

Since the early 1990s the world has experienced what some describe as an information revolution, a shift from industrial based society to one which is information based - NCW is the military expression of this change. In fact, many see the Gulf War as the watershed that marks the first conflict which was significantly dominated by information age characteristics.. [6]

NCW refers to the 'combination of emerging tactics, techniques, and technologies that a networked force employs to create deceive warfighting advantage.'[7] NCW acts as an enhancing principle to accelerate the ability to know decide and act by ' linking sensors, communication systems, and weapons systems in an interconnected grid.'[8] It is based on a variety of information technologies that should allow commanders to rapidly analyze

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[3] See: US Army, FM 1982 Operations pp.
[4] See for example US Army FM 2003 Command pp.
[5] The British version Network Centric enable, emphasizing that technology is only an enabler
[6] See discussion in Alvin and Heidi Tofler , War and Anti War (US: Little Brown & Co, 1993) Chapter 9.
[7] Military Transformation:' A Strategic Approach, Director of Force Transformation', Office of the Secretary of Defence, (Washington DC: Pentagon, 2003)   p. 13
[8] Ibid, p. 13

and communicate critical information to friendly combat forces and to react quicker in a hostile environment. NCW therefore offers a technical tool that further enhances the OODA loop.

However, to be able to fully exploit these advantages, new patterns of behavior and forms of organizations are required. The new focus is on access and speed of information, sharing information and collaboration, therefore a radical transition from the traditional top down hierarchal organization is required. Instead NCW would best suit flat, networked organizations.[9]

The changes NCW introduces can be described through the three main domains it influences:

- The Physical Domain – This represents the traditional dimension of war which includes forces moving through time and space.
- Information Domain – This is where information is being created, manipulated, and shared, including command and control and intent.
- Cognitive Domain- This is what goes inside the mind of each individual, or in other words, how each individual interpreters the world around him. It includes moral, leadership, experience, and situational awareness.

The required attributes and new capabilities of any joint force capable of conducting network-centric operations must be carefully considered for each of these three main domains. Combined synergetic effect of three domains stands in the core of the NCW concept and provides three distinct advantages: [10]

- Forces achieve information superiority and as a result develop better understanding of their own situation *vis* a *vis* their enemy situation
- The need to aggregate people to create mass becomes obsolete, instead, improved ability to disperse forces using speed and precision over greater geographical distances.
- Improved command and control and as a result a rapid OODA loop.

According to theory, NCW organizations should adhere to a number of principles in order to fully exploit the information advantage. Each advantage is dependent upon a few such guiding principles:

- High quality shared awareness is achieved through the application of: a collaborative network of networks,
- Dynamic self synchronization and adaptivity sustained by skipping the traditional hierarchy when change is necessary
- Elimination of organizational boundaries and create new processes to achieve rapid effect
- Rapid speed of command achieved by turning information superiority into decision.

[9]David S. Alberts and Richard D. Hayes, *Power to the Edge: Command & Control in the Information Age* ,(US: DOD Command & Control Research Program, 2003) p. 63-4.
[10] Marked D. Mandeles, *The Future of War: Organizations as Weapons*, (Dullas VA: Potomac Books, 2005) pp. 100-1.

Above all, the overarching principle should be the ability to empower individuals at the edge of organization, where they have the most interaction with the environment and can quickly make a resounding impact on this environment. This involves expanding access to information and the elimination of unnecessary constraints to get it. It implies enhanced peer to peer interactions on all levels of the organizations. [11]
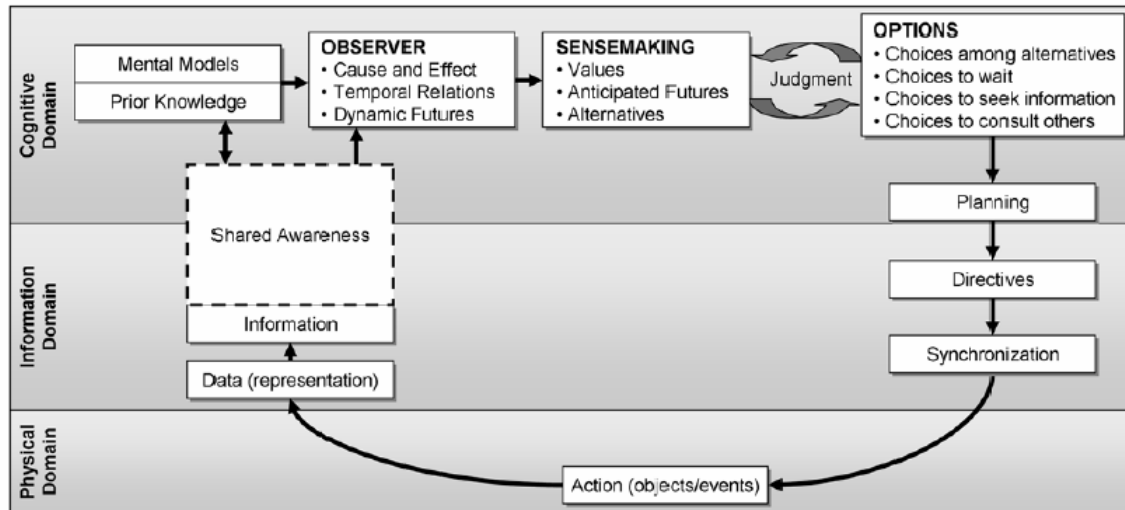

Figure 1. NCO and Effect-based Operation Action/Reaction Cycle (after Smith, 2006)

3. Conceptual Model for Decision-Making in Pharmaceutical Industry

In general, we concur with Alberts and Hayes (2007), who propose to apply NCO concepts (Figure 1) to a broader set of applications, including corporate planning and decision making. Similar to the military, an organization's ability to reconfigure quickly to exploit an opportunity, whilst retaining a robust decision-making framework that ensures overall clarity is at the heart of effective operations in corporate innovation. The Pharmaceutical industry is a prime example of corporate complexity, and we will use it to illustrate how we think the combination of concepts and tools outlined above can be used in industry.

3.1 Pharmaceutical Industry: Summary of Challenges

The business of researching, developing and commercializing a new medicine is a complex and challenging undertaking fraught with uncertainty, in which scientific,

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[11] David S. Alberts and Richard D. Hayes, *Power to the Edge: Command & Control in the Information Age* ,(US: DOD Command & Control Research Program, 2003) p. 5

technical, economic, ethical and political issues are intertwined. During the course of the process the different actors - pharmaceutical companies, academia, regulators and other government departments, contract research and manufacturing companies, pharmacies, healthcare professionals and charitable organizations – interact at multiple levels to deliver treatments to patients. Each of these groups has a specific interest in the provision of healthcare, offering fertile ground for misunderstandings, conflict and missed opportunities.
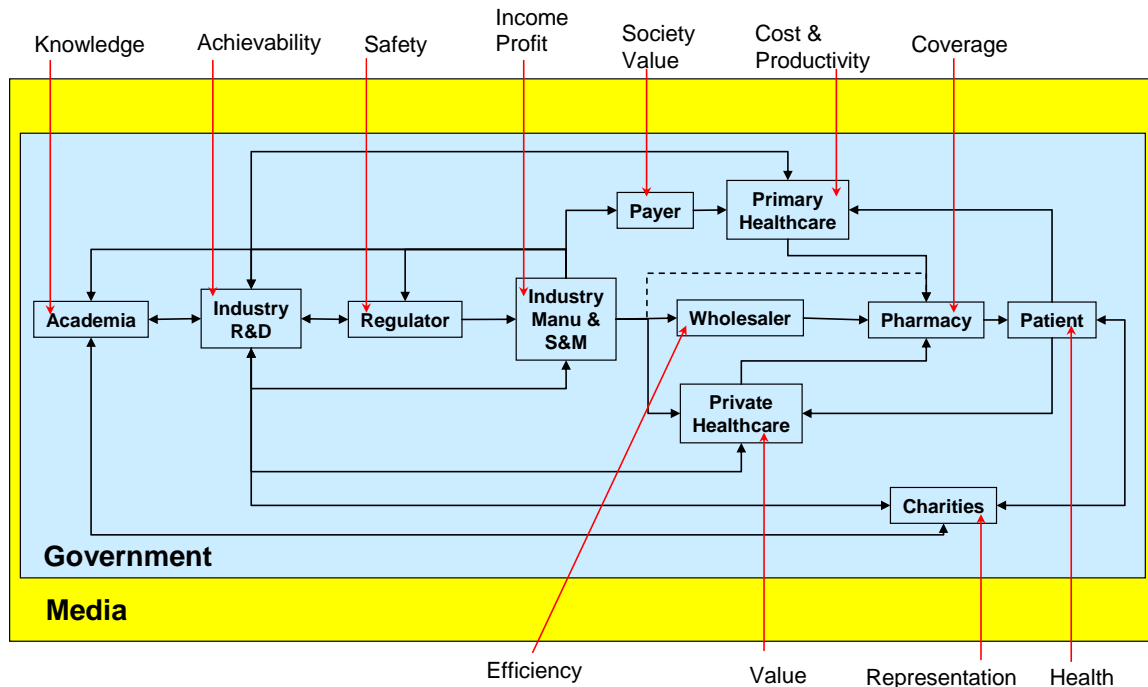

Figure 2 – Stakeholders in the Pharmaceutical Industry and different drivers for their actions.

Recent industry performance metrics put the average time to bring a medicine to the market as approximately 10 years, at an average cost of $1.2 billion – the price of a 99% failure rate in the research, development and commercialization of new medicines. For many years the industry has dealt with the huge risks by extensive consolidation, driven by business economics to exploit economies of scale and scope. Scale gives an investment tolerance to cope with the risks inherent in uncertainty and to bring to bear the expertise and technology needed to deal with complexity. Scope allows companies to access diverse technology and intellectual capacity to apply to R&D challenges. In common with most large organizations, the challenge has been to operate at scale - enabling sharing across geographies, R&D portfolios, disciplines and therapy areas – and has often resulted in inefficiency in decision-making and communication processes.

At the same time, a number of factors have conspired to move the industry towards an increasingly extreme outsourcing model. The increased availability of cutting-edge technologies and the burgeoning biotech sector, coupled with the pressure to reduce costs

in the face of falling reimbursement budgets and rising patent losses, has given rise to a dispersed 'open innovation' R&D model, with some companies going so far as to do away with traditional research and look to in-source everything. Although attractive in terms of agility and cost base, this model increases the level of complexity in the interactions that deliver the body of research required by regulatory bodies to allow them to give a confident approval for a new medicine.

It is in this environment that R&D teams must discover and/or develop new medicines. The traditional corporate command and control structure may provide clear reporting lines, but can predispose an organization to follow bureaucratic, prolonged decision-making processes. Multi-disciplinary teams have been used as a means of increasing organizational agility, but multiple reporting and approval responsibilities have the potential to destroy that agility. Either model (or combination thereof) has the potential to create decision conflicts. Understanding the decision and communication boundaries between multiple organizations provides an operating framework for complex collaborations to succeed.

3.2 Application of Mission Command in Pfizer – Lesson Learned

Like the human body, an organization is a complex adaptive system. Everything in it is related to everything else. Chains of causality are not linear. Picking the right point of leverage in the organization was similar to designing a treatment for a patient with a variety of symptoms. We had a treatment but had to decide upon the route of administration and dosage level. We decided to administer mission command locally because we did not know all its effects. Administering it generally would have taken a long time and risked rejection. We chose to administer it to select project teams in full development because they were where the potential leverage was greatest, being the point where strategy and operations meet. They represent the main axis of value creation.

The 'dosage' level we decided on was a set of two three day workshops run by a small team which specializes in introducing mission command to business. The workshops spent one day on teamwork and behaviour, and one and a half days on analysing the teams' mission. The initial pilot was run with two teams whose leaders were keen to try it out.

Early indications are that applying the principles of mission command in the pharmaceutical business is both safe and effective. The teams involved both responded very positively, and have reported far higher internal alignment and engagement with their projects. Clarifying their mission proved to be surprisingly valuable, resulting in what one project leader called "a real sense of clarity about what we needed to deliver and why." Internal structures have been simplified, meetings have been streamlined and levels of accountability have increased.

People are beginning to believe that they really are empowered to take decisions and are therefore starting to take them. One of the teams achieved a filing deadline, which at the

beginning of the year was regarded as a forlorn hope with no more than a 10% chance of success. Another has taken a full three months out of its timeline.

The methodology also appears to be safe. It can be integrated with our existing planning systems without causing disruption and does not involve costly new systems. The metrics the teams use to track their missions can be derived from our balanced scorecard. People are not abusing their freedom or running wild. One side-effect of the increased focus on the main effort of getting drugs to patients has meant that commitments to internal projects have suffered, and time allocation decisions have been more in favour of the project teams. However, the business has showed no signs of suffering as a result.

This initial treatment has highlighted the need to adjust and re-align the environment in which teams operate. There are implications for goal setting, performance management, budget responsibility, governance and approval processes — indeed our whole operating model. We can address these issues as we go, and have already started to do so. Mission command is increasingly setting our agenda.

As a next step we are running more teams through the workshops and have now launched an empowerment code which legitimizes the principles of mission command throughout our Sandwich, UK, site. We have realized that this is not just about running some team-building workshops, but about changing our operating model and aspects of our culture. The one certainty about that is that it will take a long time. But then we are used to that. We are not certain what the operating model will look like, or how the culture will develop e develop, but we do know what the main principles behind both of them are. The rest is uncertain. But then, we are used to that too. We are looking forward to the journey.

3.3 Physical, Information, Cognitive and Social Domains in Pharmaceutical Industry

The emerging environment of complex collaborations described above increases the importance of setting criteria to drive the collection, reporting and use of information for operational decision-making. Three domains (Physical, Information and Cognitive) discussed in NCO literature provide a convenient way of thinking about the decision process, not only in the military but also industry. Table 3 compares and contrasts definitions of these three domains in military and in biotech/pharmaceutical industry.

Domain	**Military**		**Biotech/Pharma**	
Physical	Theater of war Logistics Weapon systems	Physical infrastructure Social Environment	Global Markets Supply chain Laboratories	
Information	Military Intelligence, military communication networks, military information/management		Competitor Intelligence, corporate communication networks, corporate information/management	

		systems, databases/manuals		
Cognitive		Long-term strategic objectives		
	future strategic dominance clear purpose, straightforward allegiances (flag, regiment, service) single task/orientation Standardized military education Staff Interoperability Standardized personnel roles Sense of history and continuity Societal recognition		future market position complicated goals complex allegiances (industry, company, department, site, group) dynamic multitasking different science background Specialized expertise/ difficult to replace Individualized work styles/approaches Discontinuous careers Materialistic goals	

Table 3. Attributes of Cognitive, information and Physical Domains in Military and Pharmaceutical Industry

5. Implementation Roadmap

We believe that tools of risk assessment, multi-criteria decision analysis and mental modeling could be operational in transitioning pharmaceutical industry from hierarchical structure to edge organizations. Risk assessment provides quantifiable and intuitive description of actions and stimulus happening in physical domain. Through networked information domain, risk information can be transferred into cognitive domain. Mental modeling would allow efficient information assimilation and sensmaking to initiate decision-making process. Full-scale implementation of mental modeling will allow efficient communication, including cross-cultural and cross-disciplinary communication. Multi-criteria decision analysis would provide foundation for adaptive assessment of risk and other criteria and also for influencing actions in physical domain through selection of appropriate management alternatives. All this assessment takes place and is influenced by Social Domain (Smith, 2006) which encompasses socio-political and/or business environment where decision take place.

5.1 Risk Assessment for Physical Domain Representation

For centuries, the aim of planning and wargaming within a military setting has been to understand and prepare for the potential outcomes of an action, knowing that some outcomes are more likely than others. Similarly, investment/portfolio decisions in business are getting to be increasing complex and multivariate. *Risk* refers to the likelihood or probability for an adverse outcome. The concept of risk is applicable to an infinite set of decision problems in both military and corporate environment. Over the last several decades, the field of *Risk analysis* encompassing methods for developing an understanding of the processes shaping the scope and nature of risks and uncertainties has evolved. The types of questions germane to risk analysis include:

- What are the risks?
- Why and how are the risks occurring?

- How do the risk management alternatives under consideration differ in terms of risk reduction performance?
- What is the uncertainty associated with the analysis?

Risk analysis is composed of four elements: 1) Hazard identification and characterization, 2) effects assessment, 3) risk characterization, and 4) risk management. While the terminology and specific tools that are applied to risk analysis vary across disciplines (e.g., military, medicine, engineering, environmental management, economics, etc.), these four elements describe activities common to the majority of applications.

Hazard identification and characterization involves description of the nature of the events initiating and quantification threat leading to the risks under consideration. Effects assessment involves characterization of the consequences resulting from the threat. Risk characterization integrates information about the likelihood/probability of events, or families of events, with information about consequence processes to produce a description of the likelihood for specific outcomes. Risk management concerns itself with answering questions related to evaluating what actions can be taken to reduce the risks (i.e., the probability for adverse outcomes).

5.2 Mental Modeling and Sensmaking in Cognitive Domain

Risk descriptors of Physical Domain reach Cognitive domain where individual assess it. This sensmaking steps is routed in individual cognition. Efficient sensmaking and further decision making step requires understanding of cognitive basis for sensmaking. We propose Mental models as a tool which may be used to map cognitive drivers and corporate culture of different groups and then establish cross-group communication. Mental models are a complex web of deeply held beliefs that operate below the conscious level to affect how an individual defines a problem, reacts to issues, learns, and makes decisions about topics that come to their attention through communications. Mental models have been the focus of extensive research (Morgan et al., 2002; Atman et al., 1994; Bostrom et al., 1992). It is well established that people's mental models vary in important but often unpredictable ways, strongly affecting their decision processes (Fischhoff and Downs, 1997). Research has demonstrated that the complexity of people's thinking makes it impossible to predict the effects of communication on people's mental models without empirical testing.

Mental models are often used to conceptualize shared cognition, which has been shown to be an essential component of team effectiveness (Salas & Cannon-Bowers, 2001). Shared cognition focuses on peer learning and can be utilized in multiple contexts and multiple disciplines. Shared mental models may influence individual and team performance through their impact on members' ability to engage in coordinated actions. Team members with similar knowledge bases and cognitive mechanisms are more likely to interpret information the same way and to make accurate projections about each other's decisions and actions. The mental models approach to developing a sensemaking process and communication entails five steps:

Step 1:Expert Model (or Integrated Assessment)	Identify the relevant aspects of a problem (in this case, specific strategies recommended for reducing PTSD impacts)
Step 2: Lay Model Interviews	Characterize how members of the target audience frame and understand the problem
Step 3: Lay Model Survey	Quantify the prevalence of beliefs and misconceptions revealed in the interviews in the target population
Step 4: Comparative Analyses of Lay and Expert Models	Identify where members of the community need more information or guidance negotiating and implementing strategies (in this case, to reduce PTSD impacts).
Step 5: Design and Implementation of Intervention	Design intervention based on these systematically identified targets, aiming to improve understanding, decision making, and negotiation, in order to reduce risk.

5.3 Information Aggregation and Decision Making within MCDA Framework.

Multiple streams of information originating from physical domain and sensed through the prism of mental modeling in cognitive domain and external environment of social domain

need to be translated into actionable alternatives. The alternatives should be prioritized and implement as actions in the Physical domain. As with any new technology or science, developing a framework for resource prioritization and selection and making management decisions with uncertainty and incomplete information is the current challenge for industry. Risk is just one factor in making decision in real-time situations. Making efficient management decisions requires an explicit structure for jointly considering the pros and cons of a decision, along with the associated uncertainties relevant to the selection of alternative courses of action. Integrating this heterogeneous and uncertain information demands a systematic and understandable framework to organize scarce technical information and expert judgment. Our current work for EPA and DoD (Linkov *et al.*, 2006a) shows that multi-criteria decision analysis (MCDA) methods provide a sound approach to the management of heterogeneous information and risks. The advantages of using MCDA techniques over other less structured decision-making methods are numerous: MCDA provides a clear and transparent methodology for making decisions and also provides a formal way for combining information from disparate sources.

MCDA refers to a group of methods used to impart structure to the decision-making process to address complex challenges. Generally, these decision analysis methods consist of four steps: (1) creating a hierarchy of criteria relevant to the decision at hand, for use in evaluating the decision alternatives, (2) weighting the relative importance of the criteria, (3) scoring how well each alternative performs on each criteria, and (4) combining scores across criteria to produce an aggregate score for each alternative (Linkov et al., 2005). Most MCDA methodologies share similar steps 1 and 3, but diverge on their processes for steps 2 and 4 (Yoe, 2002). A detailed analysis of the theoretical foundations of different MCDA methods and their comparative strengths and weaknesses is presented in Belton and Stewart (2002).

We propose to follow a systematic multi-criteria decision analysis (MCDA) framework developed by Linkov *et al.* (2007) for alternatives generation and selection. A generalized MCDA process will be adjusted for the corporate. It will follow two basic themes: (i) generating alternative management options, success criteria, and value judgments and (ii) ranking the alternatives by applying value weights. The first part of the process generates and defines choices, performance levels, and preferences. The latter section methodically prunes non-feasible alternatives by first applying screening mechanisms (*e.g.*, significant risk, excessive cost) and then ranking, in detail, the remaining alternatives by MCDA techniques that use the various criteria levels generated by models, experimental data, or expert judgment. While it is reasonable to expect that the process may vary in specific details among applications and project types, emphasis should be given to designing an adaptive management structure that uses adaptive learning as a means for incorporating decision priorities.

The tools used within group decision making and scientific research are essential elements of the overall decision process. The applicability of the tools is symbolized in Figure 2 by solid lines (direct involvement) and dotted lines (indirect involvement). Decision analysis tools help to generate and map technical data as well as individual

judgments into organized structures that can be linked with other technical tools from risk analysis, modeling, monitoring, and cost estimations. Decision analysis software can also provide useful graphical techniques and visualization methods to express the gathered information in understandable formats. When changes occur in the requirements or the decision process, decision analysis tools can respond efficiently to reprocess and iterate with the new inputs. This integration of decision, scientific and engineering tools allows users to have a unique and valuable role in the decision process without attempting to apply either type of tool beyond its intended scope.

Three basic groups of stakeholders include managers and decision-makers, scientists and engineers, and stakeholders. These groups are symbolized in Figure 2 by dark lines for direct involvement and dotted lines for less direct involvement. While the actual membership and function of these three groups may overlap or vary, the roles of each are essential in maximizing the utility of human input into the decision process. Each group has its own way of viewing the problem, its own method of envisioning solutions, and its own responsibility. Managers spend most of their effort defining the problem's context and the overall constraints of the decision. In addition, they may have responsibility for final alternative policy selection. Technology recipients may provide input in defining alternative nanomaterials and nanomedical alternatives, but they contribute the most input by helping formulate performance criteria and making value judgments for weighting the various success criteria. Depending on the problem and context, patients and users may have some responsibility in ranking and selecting the final nanomaterial use alternative. Scientists and engineers have the most focused role in that they provide the measurements or estimations of the desired criteria that determine the success of various nanomaterials and alternatives.
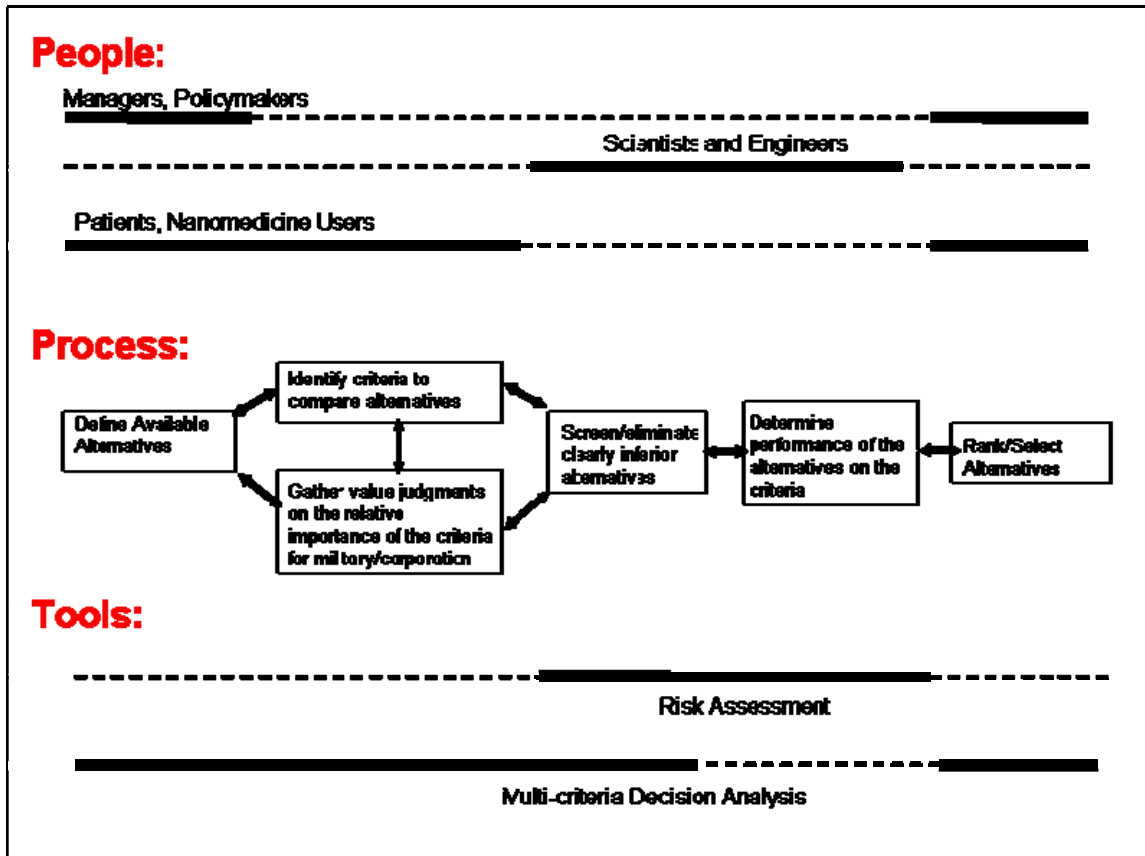
Figure 2: Example decision process. Dark lines indicate direct involvement / applicability and dotted lines indicate less direct involvement / applicability.

The result is a comprehensive, structured process for selecting the optimal alternative in any given situation, drawing from stakeholder preferences and value judgments as well as scientific modeling and risk analysis. This structured process would be of great benefit to decision making in management, where there is currently no structured approach for making justifiable and transparent decisions with explicit trade-offs between social and technical factors. The MCDA framework links heterogeneous information on causes, effects, and risks for different nanomaterials with decision criteria and weightings elicited from decision-makers, allowing visualization and quantification of the trade-offs involved in the decision-making process. The proposed framework can also be used to prioritize research and information-gathering activities and thus can be useful for the value of information analysis.